Neutron activation for ITER

Cris W. Barnes
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Michael J. Loughlin
JET Joint Undertaking, Abingdon, United Kingdom

Takeo Nishitani
JAERI Naka Fusion Research Establishment, Naka, Ibaraki 311-01, Japan

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There are three primary goals for the Neutron Activation system for ITER: to maintain a robust relative measure of fusion power with stability and wide dynamic range (seven orders of magnitude), allow an absolute calibration of fusion power production, and provide a flexible and reliable system for materials testing. The nature of the activation technique is such that stability and wide dynamic range can be intrinsic properties of the system. It has also been the technique that demonstrated (on JET and TFTR) the most accurate neutron measurements in DT operation. Since the detectors for assaying the radioactivity are not located on the tokamak and are therefore amenable to accurate characterization, and if the activation samples are placed very close to the ITER plasma with minimal scattering or attenuation, high overall accuracy in the fusion energy production (7%–10%) should be achievable on ITER. In the paper, a conceptual design is presented. A system is shown to be capable of meeting these three goals, and unresolved design issues are identified. © *1997 American Institute of Physics.* [S0034-6748(97)57001-8]

I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is intended to be a long-pulse burning plasma experiment capable of providing the physics and technology database necessary to implement a demonstration fusion reactor. The 1.5-GW fusion power device will place extreme requirements on its plasma diagnostic systems. Central to the mission of the machine is the ability to accurately and precisely monitor the fusion power. This can be achieved by using the neutron activation technique whereby a sample of material is placed close to the neutron source (the plasma). It is then retrieved and an estimate of the total neutron production can be made from an assay of the radioactivity induced in the sample by the fluence of neutrons incident upon it. This is usually done using gamma-ray detectors, but neutron detectors have been used when the activation sample was a fissile material. Neutron activation has been the technique that demonstrated (on the JET[1] and TFTR[2,3] tokamaks) the highest accuracy neutron measurements in DT operation, and without the need for *in situ* source calibration. This paper describes issues relevant to a conceptual design for a neutron activation system for ITER.

There are three primary goals for the neutron activation system on ITER:

(1) Maintain a robust relative measure of fusion power with stability and wide dynamic range.
(2) Allow an absolute calibration of fusion power production.
(3) Provide a flexible system for materials testing. Such materials testing can include accurate measurements of some weak reactions previously not accessible on present neutron sources at accelerators.

The neutron activation technique is intrinsically stable and linear with respect to fusion power level. Activation coefficients (the number of activated nuclei per target nuclei per source neutron) are of the order of 1.0×10^{-31}. Therefore, even for a source of 1.0×10^{21} neutrons, ''saturation'' of the sample and effects of secondary reactions can be ignored. However, it is important to ensure the linearity of the gamma-ray detectors by avoiding problems of dead-time or pileup. This is done by appropriate selection of sample material and mass and a suitable detection efficiency as discussed in Sec. II A.

There are two problems in accurately determining the total neutron yield and fusion energy production from neutron activation. First, there is the problem of the ''efficiency'' of the neutron activation detectors, which can be separated into two parts: the activation cross-sections, which are ''physical'' and unchanging and (for dosimetric reactions) are well known with quantified uncertainties; and then the efficiencies of the gamma-ray detectors which can be accurately determined and tend to remain stable since the detectors are remote from the tokamak. The second problem is that of determining the neutron spectrum and fluence at the activation position for a given total yield. This problem has succumbed to operating with samples in close proximity to the plasma and to careful neutronics modeling.[4] Assuming that materials can be placed very close to the ITER plasma with minimal scattering and attenuation, we should be able to achieve similar 7%–10% accuracy on ITER in the neutron production measurement. How this is to be achieved is discussed in Sec. II B.

The reliability and flexibility of the system are essential if the system is to provide a useful materials test-bed. These are primarily engineering considerations but are nontrivial because of the unprecedented high radiation fluxes and unique access difficulties at ITER. These issues are ad-
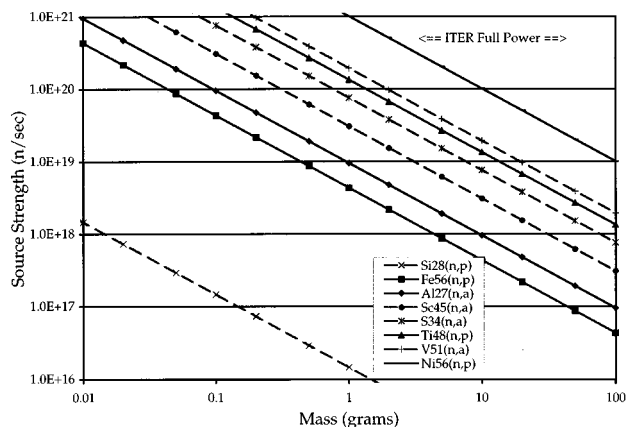
FIG. 1. Source strength required to create 100 μCi of activity in a 100-s exposure for a given mass of material. Irradiation location at top of machine (foil radius 8.7 m, foil height 6.0 m, poloidal angle 85°). Reactions are listed from most sensitive to least. Dosimetric reactions have solid lines, reactions with uncertain cross-section have dashed lines.

dressed in Sec. II C. Other design considerations are discussed in Sec. III.

II. SYSTEM REQUIREMENTS

A. Response sensitivity and mass of foils

Given the higher fusion power level and assuming irradiation locations near the surface of the blanket/shield modules, despite the larger size of ITER the expected activation rate is about ten times greater *per second* than on present-day DT tokamaks. To reduce the level of activation, less mass can be used; however, there is a minimum practicable amount of sample mass (or sample mass density in a fluid system) that one can use before contamination becomes an issue.[5] Removing the irradiated sample material from the encapsulation for counting can mitigate contamination, but with significant engineering issues to avoid personnel dose. One cannot choose to use arbitrarily small cross-section reactions as they are not dosimetry standards and one looses the absolute calibration. Furthermore, one gains only about a factor of 100 in sensitivity before signals are overwhelmed by competing reactions. Thus very radioactive samples will be produced. If we use short half-life activities, then the samples are very hot (must be counted far from detectors which can be problematic). If long half-life (10^6–10^8 s) activities are used the samples cannot be re-used and a modest waste problem is created. Samples which create products with half-lives of the orders of hours or days are appropriate. An equilibrium is not reached between activation rate and decay rate, as would happen if the irradiation period was longer than the half-life, and long-term excess radioactivity is avoided. For 1% efficient detection of the gamma-rays from such reactions the masses required to provide appropriate count rates appear reasonable.

The activation desired for a sample should be similar to that provided by a standard source used for absolute calibration of the gamma-ray detectors. A typical maximum value for modestly safe handling would be 100 μCi. Figure 1 shows the source strength of neutrons needed to create
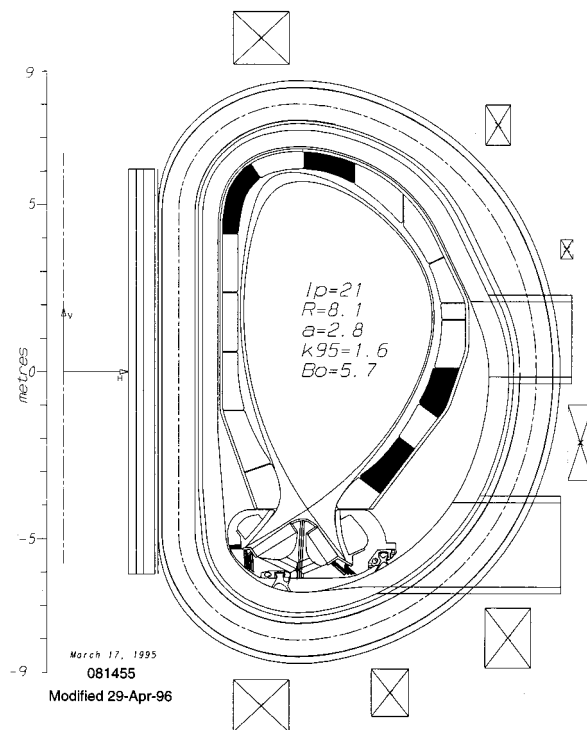

FIG. 2. Cross-section elevation of ITER. Shaded regions show suggested locations of activation irradiation ends.

100 μCi samples assuming 100-s exposures for various reactions at a typical location on ITER. Operation at low mass (to the left of the figure) is problematic because of contamination. Above 100 g, the self-absorption of the samples and the increased and varying sample-detector distance makes adding mass ineffective, and the calibration loses accuracy. The silicon reaction is too sensitive but would be useful at low power and during deuterium-only operation for the study of triton burn-up, for example. The nickel reaction is very long-lived (70 days), but iron, aluminum, and titanium foils appear to allow for reasonable sensitivity without creating sources which are too intense, especially if samples may be sent and retrieved during the discharge to limit the exposure duration. Other nondosimetric reactions of smaller cross-sections can also be used after cross-calibration.

B. Location of irradiation ends

The neutron activation technique must be able to provide an accurate and precise measurement of the total neutron emission without the need for *in situ* source calibration. The precision can be calculated, but the accuracy (the avoidance of systematic errors) must be demonstrable. To this end the location of the irradiation ends must be carefully selected with regard to sensitivity to plasma position and neutron emission profile using neutronics calculations.

On TFTR, with a circular plasma held in the midplane, it was relatively easy to maintain insensitivity to the profile and position of the neutron emitting region. There was a ~15% decrease in signal from the single re-entrant irradiation end on the top of TFTR following an increase in plasma major radius of ~0.6 m.[4] Any toroidal variation of the neutron
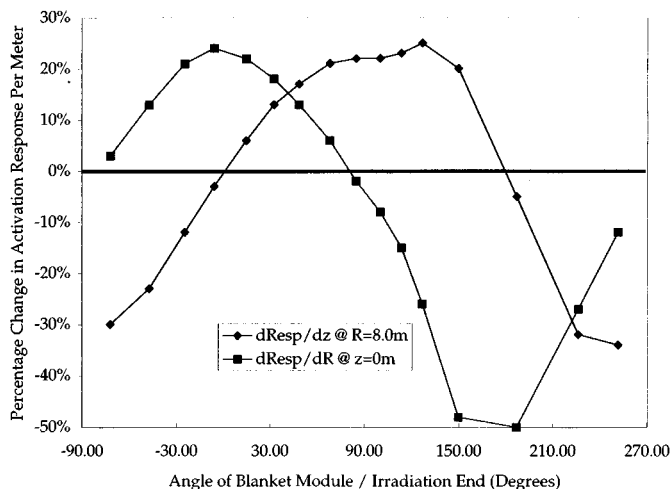
FIG. 3. Percentage change in activation response per meter as toroidal line source of neutron emission is moved. The diamonds are caused by variation in the z direction, and the squares are for variation in the R direction. Zero degrees is the outboard midplane.
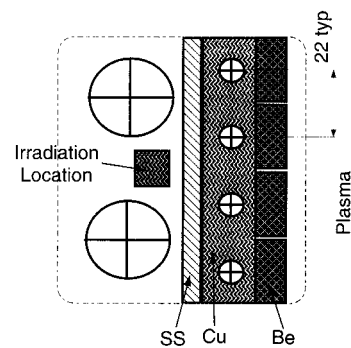

FIG. 4. Typical cross-section of materials on ITER blanket-shield module first wall. The scale is set by the typical 22 mm between first-wall cooling pipes and the 1 cm×1 cm irradiation location for activation.

fluence can be ignored. Multiple measurements at different poloidal locations are needed for ITER because of the asymmetric, elongated plasma. Figure 2 shows a cross-section elevation of ITER and the location of the blanket/shield modules. As on JET, ITER will probably need three poloidal locations instrumented for neutron activation with a fourth for redundancy. Another set of irradiation ends at a different toroidal location (for eight total irradiation ends) would also be desired for redundancy against failure.

The sensitivity of locations at each module to movement of the neutron emitting region can be estimated analytically. The approximation that the neutrons are emitted from a toroidal line source is a relatively good one.[6] While the absolute value of the activation response depends on detailed scattering calculated from neutronics models, the relative trends of the response as the plasma source is moved follow the analytic formula of Zankl[6] quite well.[4] It is also found that the trends are insensitive to the breadth of the neutron profile. Figure 3 shows the percentage relative change in the analytic response per meter of movement of a toroidal line source for a location at the center surface of each blanket/module, plotted as the poloidal angle of the module. In general, one needs to measure in the direction of movement to be sensitive. If two irradiation ends were at $-50°$ and $110°$, then $d\mathrm{Resp}/dR$ is $+10\%$ for the first one and -10% for the second, and $d\mathrm{Resp}/dz$ is about -25% for the first and about $+25\%$ for the second. Simultaneous irradiation in these two ends would allow averages to be taken which would cancel out movements of the plasma even when both occurred at the same time. These positions avoid proximity to the divertor and the attendant problems for neutron transport calculations. Two more irradiation ends could be positioned at $0°$ (no sensitivity to dz) and $80°$ (no sensitivity to dR). These irradiation ends could be used to check $d\mathrm{Resp}/dR$ and $d\mathrm{Resp}/dz$ for the other two irradiation ends. Quite possibly, "extreme" radius or height plasmas will be run to quantify neutron camera calibrations and scattering; these should be prepared for.

Four typical blanket/shield modules that would need to be instrumented to provide up/down and in/out measurements for neutron activation are highlighted in Fig. 2.

To achieve the goal of high accuracy in the neutronics calculations requires that the irradiation positions be relatively close to the plasma. The high accuracy achieved on both JET and TFTR was only obtained after the installation of "re-entrant" irradiation ends. The thickness of material between the plasma and foil must be minimized so that activation is due mostly to the direct unscattered flux. To ease modeling, the avoidance of variation of mass density close to the irradiation position is more important than the avoidance of intervening material. Thus, a position inside a shield module may be satisfactory *if* a relatively uniform and well-characterized amount of material surrounds the irradiation end. Figure 4 shows a typical cross-section through a blanket/shield module first wall with a 1-cm^2 irradiation location. Over 25 mm of beryllium, copper, and stainless steel must be viewed through by the irradiation location. Sensitivity studies of the neutronics calculations will be needed when the designs of the blanket/shield modules are finalized. An experimental test of the reliability of the calculations can be made by using a variety of reactions with different thresholds. One desires that reactions with low thresholds should give the same results as measurements using high threshold reactions which are less sensitive to the scattered flux.

C. Material testing and system requirements

In addition to providing a calibrated signal, the system should also be designed for material testing. A reaction of only 1 mbarn cross-section, a year half-life, and only 5% isotopic abundance in a 10-g sample will still give over 10 cps, assuming 1% detection efficiency after exposure to a 1000-s full-power ITER discharge. Thus pneumatic capsules capable of no more than 10-g samples (similar to that used on TFTR and JET and requiring about 1 in. diam plumbing) is desired. The 2-cm ID of the support structure cooling pipes are consistent with this mass and sample size; a 1-cm ID system would also still be big enough.

The provision of a low background counting area is required. At least one detector of high efficiency and one of high energy resolution are desired for flexible purposes. The

other detectors can be simpler with lower resolution for routine measurements. Those routine measurements would have ~100 μCi activity, so again low efficiency is allowed. There must be plans to implement "renormalization" procedures and routine absolute calibration of system components.

The JET "carousel" system for switching between irradiation ends and counting stations seems the best type of solution for flexibility of operation. By placing the carousel inside the tritium containment boundary, the complex purging of pneumatic tubes and switching to remove activated air may be minimized or at least simplified. However, maintenance access to the carousel will almost certainly be required. The design of the pneumatic system should maintain a modular approach to counting room and pneumatic layout so it is easy to change and upgrade. A desirable requirement would be to engineer very fast transfer times of samples to at least one counting station. This won't be routinely needed, but strongly increases the system usefulness for materials testing and other special work. The TFTR system operates at about 10 m/s transport speed. If the counting room for the activation system is located 100 m from the tokamak, we might want an order of magnitude faster transport speed. The overall system emphasis is twofold: a robust routine operation, and an otherwise flexible system to maximize scientific usefulness.

III. OTHER DESIGN CONSIDERATIONS

Activation does a time-integrated measurement, but it will be desirable to move samples in and out *during* the ITER pulse. This will make measurements during only fractions of the shot duration, for time-dependence but primarily to avoid samples becoming too active. Moving magnetic samples (like iron) might be problematic, but the masses will be very low. Some degree of automatic computer control and monitoring of sample transfer and data-taking linked to the ITER pulse time base is needed with a documented audit trail of foil transfers. This will also require robust monitors of sample position near the machine. Some irradiation ends will require a constant flow of air to keep the samples in place. The duration the sample spends close to the plasma must be monitored during its transfer. However, the fluence drops rapidly with further distance from the plasma, and at the desired fast transfer speeds the resulting few milliseconds in transit will not affect the measurement.

The irradiation ends should be located just in the first wall (see Fig. 4, for example). If they were located back at the shield surface there would be ~122 mm of material between them and the plasma, which would cause too much attenuation. Using one of the 23-mm OD, 20-mm ID support structure cooling pipes as a transfer tube for the activation system may not be consistent with power handling needs. Also, the number and sharpness of bends in the cooling pipes are not conducive to a pneumatic transfer system, where typically the radius of curvature of any bend must be many times the length of the capsule. A special pipe may be needed, with extra cooling around it.

As mentioned before, there may be a problem with capsule contaminants and achieving low-mass samples[5] with small dose from manual handling. At the intense fluences of ITER, capsule contaminants (for example, sodium that might interfere with the $^{27}Al(n,\alpha)^{24}Na$ reaction) may provide a lower bound on the mass of the foils used. But this lower-bound mass may be too large to allow manual handling of the foils for a considerable time. Measuring and quantifying the contaminants in the capsules may be difficult given, again, the intense fluences expected on ITER. The transfer system should thus be designed to allow entirely remote handling while maintaining flexibility in the order and timing of the irradiations and counting. Careful consideration of safety issues with both hardware and procedural controls will be necessary.

Flowing or liquid-activation systems[7] have been considered. In general, the coolants in the coils or blankets are too far from the plasma to allow the required level of accuracy in such a measurement. The technique of marrying neutron activation and fluid flow is generally used as a method to use a *known* neutron source to measure fluid flow. A flowing system might be able to sample all around the plasma in a single channel and achieve some insensitivity to variations in neutron emission location. In view of the difficulties in demonstrably achieving a high level of accuracy without *in situ* calibration sources, which is the virtue of the solid activation system, we do not consider that there is a need to provide a fluid-flow activation system. The monitoring of the activity in existing cooling systems could be easily implemented and would provide an interesting comparison to the other neutron diagnostics. A test fluid-flow system in a single module or perhaps a diagnostic preshield might be a useful technology test.

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